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Experimental Large-Scale Snow and Ice Mapping With Composite Minimum Brightness Charts

E. Paul McClain and Donald R. Baker

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U.S. DEPARTMENT OF COMMERCE
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National Environmental Satellite Center

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EXPERIMENTAL LARGE-SCALE SNOW AND ICE MAPPING WITH COMPOSITE MINIMUM BRIGHTNESS CHARTS

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E. Paul McClain and Donald R. Baker

ABSTRACT

The Composite Minimum Brightness (CMB) chart is a computer product derived from digitized and rectified satellite video data. The minimum brightness values mapped over an area during a given period are composited and displayed as a means of suppressing transient cloudiness and enhancing major snow and ice features in the satellite imagery. Examples are presented, and limitations and verification of the technique are discussed.

1. INTRODUCTION

Comprehensive and repetitive survey of polar ice and snow fields would be of great benefit to atmospheric, marine, and other scientists, as well as to various military and commercial operations. This type of surveillance by sensors or human observers carried in aircraft or surface vehicles, however, would be hazardous, time-consuming, and very costly in the vast, harsh, and poorly accessible regions at high latitudes. Monitoring of snow cover and ice in coastal areas, lakes, and rivers at subpolar and middle latitudes for hydrologic and other purposes is a similar task that cannot be accomplished satisfactorily or practically by conventional means. Polar-orbiting satellites would provide a rapid and economic means for securing snow and ice information for many research and operational purposes.

Despite considerations of resolution, object illumination, and obscuration by clouds, the potential of meteorological satellite data for mapping snow and ice fields was recognized shortly after the first pictures from TIROS experimental satellites became available (Fritz, 1962; Wark and Popham, 1962). With the regular, near-global, picture coverage of the operational ESSA satellites, research and operational usage of the pictures for snow and ice mapping has greatly increased. Recent examples include work by Barnes and Bowley (1968), Bowley (1969), Potocsky (1968), and Popham and Samuelson (1965).

The techniques used to date in the application of satellite data to the charting of snow and ice boundaries and features have been basically those of simple photo-interpretation. This has involved detailed visual inspection of individual photographs, identification of landmarks, and differentiation of clouds from the sometimes similar-appearing snow or ice. Scrutiny of photographs of the same area taken on several successive days was found to be very useful for cloud discrimination because cloud masses are much more transient than snow or ice fields. With the development of satellite picture digitization and rectification procedures (Bristor et al., 1966), computer production

of picture mosaics, enhancement, compositing, and other data manipulation became feasible. This report will discuss briefly the experimental use of one of these computer products in snow and ice mapping.

2. COMPOSITE MINIMUM BRIGHTNESS (CMB) CHARTS

The details of the digitizing and computer processing of ESSA satellite video data have been given in Bristor et al. (1966) and in Bristor (1968), so only a brief description is given here. After digitization, all video data for a given day are resolved into a so-called "full-resolution" array based on the Numerical Weather Prediction (NWP) grid system of the National Meteorological Center. There are 4096 NWP grid squares in each hemisphere, and a sub-array of 64X64 satellite datum points (4096 in all) is mapped into each grid square. Thus a total hemispheric array of full-resolution satellite data comprises 4096X4096 datum points. Each datum point of the full-resolution array represents an area approximately 5 km on a side and gives a measure of the brightness of the earth's background, including clouds, on an integral scale (relative) ranging from 0 to 14. The raw data are brightness-normalized for non-linearities in response of the camera system and inequalities in solar illumination, then mapped onto polar stereographic and Mercator map projections after overlapping imagery from adjacent orbits has been cropped.

A meso-scale data array is produced from the full-resolution array by reducing the datum points by a factor of eight in each dimension (the meso-scale area is thus about 40 km on a side). In order to retain much of the original information content of the full-resolution data during this data compression step, the original relative brightness range of 0-14 is divided into five equal classes and a frequency distribution of the full-resolution population of each meso-scale spot is stored on magnetic tape. A detailed description of the tape format and of some of the computer products that can be derived from the meso-scale archive is given by Booth and Taylor (1968, 1969).

The Composite Minimum Brightness (CMB) chart is the meso-scale product that has proven the most useful in large-scale snow and ice mapping. This chart is constructed within the computer by first spatially averaging the full-resolution brightness data for each meso-scale spot; this average is computed from the brightness histogram. These average brightnesses are then composited over a selected period of days by saving only the minimum value for a given meso-scale spot during the compositing period. The resulting CMB chart is displayed on a cathode ray film device[1] in rectified form; latitude and longitude lines as well as geographic and political boundaries are added electronically (figures 1-3 and 6).

[1]Earlier charts, such as the 1967 CMB chart given in figure 2, were displayed using a compressed brightness scale of five gray shades from black through white, whereas subsequently all 15 brightness levels have been displayed. CMB charts for the period beginning Oct. 1, 1968, are available in film image form from ESSA's National Weather Records Center, Asheville, N.C. They are produced for five-day, non-overlapping periods on polar stereographic map bases of the Northern and Southern Hemispheres.

Clouds, which are often comparable in brightness to snow and ice, are retained in the CMB chart only when they are present in a given area (i.e., over a particular meso-scale spot) every day of the period. In general clouds are sufficiently transient to assure that the bright areas retained in the CMB chart represent the relatively permanent snow and ice fields. Occasionally cloudiness will be so persistent in a particular region that the CMB technique fails to filter it out completely, especially if the compositing period is short. Such time-composited cloud areas, however, usually are not so bright as composited snow and ice fields. The optimum number of days for the compositing period is a compromise between a period long enough for effective cloud filtering and one short enough to minimize the effects of time-changes in the ice or snow boundaries. Also the operational usefulness of the charts is impaired if the period is too long. Trials indicate that the minimum effective compositing period is three days, and the maximum useful period is about seven.

It should be kept in mind that errors in the location of imagery in individual frames can arise from picture time errors and satellite attitude errors. Bristor (1968) states that "although positioning accuracy is usually good to within 5-10 miles, errors up to about 30 miles may occur near the subsatellite point and perhaps double that amount in the foreshortened regions near the horizon." Consideration of the meso-scale data compression and multi-day compositing procedures would indicate that location accuracies in the CMB charts should be of the same order as the original full-resolution data. This is confirmed by checking those coastlines where there is a good brightness contrast between snow-covered land and open oceans and the electronically-superimposed coastlines.

3. EXAMPLE OF SNOW MAPPING WITH CMB CHARTS

Three periods in 1967 were chosen for verification purposes: February 17-23, March 2-8, and March 21-27. Seven-day composites were available for all three periods, and three- and five-day composites were derived for the first period. In addition some experimental average brightness charts for three- to seven-day periods during February 17-23 were derived photographically from daily, full-resolution digital mosaics by essentially the same multiple-exposure method used by J. Kornfield et al. (1967).

Daily ground observations of snowfall and snow on the ground, compiled and published monthly for each State in the United States in ESSA's Climatological Data series, were used for comparison purposes. Observations of depth of snow on the ground were plotted for each day of the specified periods for the area east of the Rocky Mountains. To define a single major snow boundary for each compositing period, it was necessary to find a way to composite the ground observations also. It was reasoned that the envelope of stations reporting one inch or more of snow on the ground every day of the compositing period would delineate the appropriate major snow boundary. If there was no snow cover in a given area for even one of the days of the period, that area should appear dark in the CMB chart (unless it was covered with cloud on that day).

The February 17-23, 1967, period was the subject of the most extensive experimentation. Three-, five-, and seven-day CMB charts were derived by

computer (figures 1, 2, and 3), and average brightness charts for the same sets of days were obtained using the multiple exposure method (only one of these is reproduced--figure 4). Comparisons of CMB charts for the various compositing periods show that those clouds retained in the three-day composite are either eliminated or suppressed in brightness in the five-day composite. A lesser amount of additional cloud filtering is effected when the compositing period is lengthened to seven days. It should be noted that the western North Atlantic was characterized by unusually persistent cloudiness during this period.

Figure 4 is a portion of the 5-day average brightness chart derived by the multiple-exposure method. Although this technique produces an image with considerably higher resolution and a greater tonal range than the computer method used in 1967, painstaking photographic processing is necessary to achieve the required accuracy in both registration and exposure of successive images. Furthermore, average brightness charts are inferior to CMB charts in cloud filtering (e.g., compare figures 2 and 4 in the region south of the snow line).

Obvious errors in the positioning of the imagery in figures 1-4 appear in the vicinity of Lake Michigan and Lake Huron. By reference to these and other identifiable features of known location,[2] it was found that the datum points in the daily ESSA 3 digitized charts and in the composite or multiple-exposure charts derived from them are evidently, and consistently, mislocated too far north and too far west by about one-half degree of latitude (55 km) and longitude (about 35 km at 40° N.) respectively. This location error apparently is introduced during the computer mapping process, since errors in the location of the same landmarks in the undigitized AVCS pictures generally are less in magnitude and not as consistent in direction as those found in the digitized products. Inspection of more recent digitized pictures and composite charts based on ESSA 7 and 9 video data indicates that this systematic positioning error has been reduced to 35 km or less.

Figure 5 is a chart of snow-on-the-ground derived from ground observations for the February 18-22 period. The plotted values indicate where amounts of 1 inch up to 20 inches of snow were observed every day of the period. The hatched area designates the zone of uncertainty in the placement of the ≥1 inch line[3] from these ground observations. In a few places even the boundaries of this zone are somewhat uncertain because of missing reports or widely separated observation points. The correspondence between this chart and the CMB chart for the same period (figure 2) is discussed below.

The bright area in figure 2 whose southern boundary runs generally east-southeastward across South Dakota, Iowa, and northern Illinois, thence northeastward across Indiana into southeastern Michigan, corresponds rather closely to the major snow area covering the northern portions of the Midwest and Great Plains (after corrections are made for the systematic gridding error

[2] The report by Cronin (1963) and the discussion of landmarks in Barnes and Bowley (1968) were of considerable help in this connection.

[3] The ≥1 inch criterion is based on the operational guide developed by Barnes and Bowley (1968).

just discussed). In view of the inherent uncertainty of determination of the ≥1 inch line from ground-based observations, and a possible error of up to half a meso-scale grid interval (i.e., 20 km) in defining the transition from a bright snow area to a dark snow-free one, it is gratifying that the boundary interpreted from the CMB chart falls largely within the zone of uncertainty in figure 5.

The greatest discrepancies between figures 2 and 5 occur near 94.5° W. (north-central Iowa), 97.5° W. (southeastern South Dakota), and 87.5° W (northeastern Illinois). In each of these areas the CMB chart (figure 2) indicated no snow, whereas analysis of the ground observations indicated that snow was present. In all three of these areas the data permitted more than usual latitude for placement of the boundaries of the zone of uncertainty in figure 5, and this factor may be a partial explanation. More important, however, is that examination of the individual, full-resolution satellite pictures during the compositing period revealed that on at least one of the days all or part of the doubtful areas appeared dark. This definitely indicates that these areas were free of clouds <u>and</u> snow cover on those days, and an area that appears dark on even <u>one</u> day of the compositing period must appear dark on the CMB chart. <u>Finally</u>, the representativeness of the ground station reports in relation to the meso-scale resolution of the CMB chart imagery also must be taken into account. That is, snow or snow-free areas whose dimensions are smaller than about one-half degree latitude will be poorly represented in a meso-scale CMB chart, since the CMB chart is based on <u>average</u> brightness for areas of this size. This factor is more readily appreciated if one examines figure 4, which is the full-resolution, multiple-exposure chart. Note particularly how this chart shows rather small-scale details such as the narrow band of snow around the southern tip of Lake Michigan and the small tongue of snow cover extending southwestward through southeastern Iowa. These features are absent from the CMB chart of figure 2 because of its coarser resolution and compressed gray scale. Incidently, it is seen from figure 5 that the snow tongue analyzed in Iowa is based essentially on a single report of ≥1 inch of snow on the ground throughout the period.

Although the 5-tone meso-scale CMB chart generally is effective in delineating the main snow line in the Great Plains and in the relatively unforested areas of the Middle West, it is less effective or totally ineffective in heavily-forested areas such as the upper Great Lakes, the southern portions of Ontario and Quebec, and much of the northeastern United States and Appalachian Mountains. Some of the rather irregularly distributed snow areas through Pennsylvania and New York are detectible in figure 2, but the tones are darker than in the Midwest because of fewer large areas of cleared farm land and the many, largely deciduous, forests. One fairly large snow-covered conifer area, the Adirondacks in northeastern New York State, appears black in figure 2, and there are only slight indications of the fairly large (albeit rather shallow) snow area in the Appalachian Mountains of West Virginia and Virginia.

Conover (1965) and Barnes and Bowley (1968) point out that, in general, the denser and more extensive the stands of trees, particularly if the trees are predominantly coniferous, the darker the area will appear, even when snow

of considerable depth is present.[4] Thus, with the exception of the St. Lawrence Valley, virtually none of the snow present in the main coniferous forest belt across the southern portion of eastern Canada, or in New England, is discernible in the CMB charts of figures 1-3; with only five gray levels resolved, these areas appear mostly black. Since it is often possible to distinguish between forested areas that are snow covered and those that are not in the individual, high-resolution pictures (digitized or undigitized), part of the difficulty with the meso-scale composites evidently stems from their coarser resolution and the inevitable "smear" resulting from compositing successive pictures with slightly different location errors. The compressed gray scale in figures 1-3 also aggravates the situation, especially in the darker-appearing conifer areas. For example, when the main conifer belt of southern and eastern Canada is snow-covered, it has a medium to dark gray appearance in the more recent 15-tone meso-scale CMB charts. In the daily, full-resolution, digitized pictures this same area characteristically appears as a dark gray background mottled with numerous small, irregularly shaped white spots, most of which are frozen, snow-covered lakes. Although somewhat smeared due to registration difficulties in the multiple-exposure process, this appearance is partially preserved in figure 4.

In figures 1-4, the very light gray areas in central Quebec, northern Ontario, and northern Manitoba correspond generally to the region designated "northern subarctic forest (without fir)" (Canada, 1957); the brighter-appearing snow-covered ice on Hudson Bay and the snowy tundra lie farther north. Equally bright are the plains and prairie areas of Saskatchewan and Alberta. The coniferous belt extending westward through the northern portion of these provinces has a rather mottled appearance, especially in the 5-tone CMB chart (figure 2), suggesting an irregular distribution of forest types or land use.

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[4] This is in sharp disagreement with Cronin (1963), who makes the generalization that the coniferous forest belt in southeastern and south-central Canada appears lighter, not darker, in tone than the largely deciduous forest zone adjacent to it on the south when both of these are snow covered. He makes a similar generalization about such forested mountain areas as the Adirondaks and Catskills of New York State, the Green Mountains of Massachusetts and Vermont, and the White Mountains of New Hampshire. Morrison and Bird (1964), however, have illustrated clearly that when snow is on the ground <u>throughout</u> a region the coniferous forest areas in satellite pictures <u>appear darker</u> than their surroundings. They also show, on the other hand, that when the snow melts in the relatively unforested lowlands while remaining at the higher elevations, these forested highlands then appear <u>lighter</u> than the neighboring valley areas. Conover (1965) illustrates another, considerably rarer, meteorological situation that could produce this type of contrast, viz., when wet snow clings to the tree crowns in the mountains, usually in combination with rain in the valleys. Close examination of all the cases presented by Cronin in support of his thesis, together with ground observations of snow depth and temperature, indicates clearly that what Cronin interpreted as the deciduous-coniferous boundary was actually the snow line itself. The deciduous areas appeared darker than the coniferous merely because there was little if any snow present in the former.

The snow-covered higher elevations (generally above the tree line) of the Canadian and American Rocky Mountains and of Canada's Coast Mountains appear fairly bright in all the CMB charts, but the snow present on the lower, more heavily-forested slopes generally is not discernible in the 5-tone meso-scale composites (figures 1-3).

Comparison of meso-scale 7-day CMB charts and multiple-exposure, average brightness charts for March 2-8 and March 21-27 with the corresponding snow cover charts based on ground observations (charts not reproduced) gave results similar to those just discussed in detail for the February 18-22 period. As before, the snow line was generally well-defined except in heavily-forested or mountainous terrain, and the accuracy in positioning the snow line was within the limits of uncertainty in placing the line from analysis of surface reports.

4. EXAMPLE OF SEA ICE MAPPING WITH CMB CHARTS

The use of meso-scale CMB charts for large-scale mapping of sea ice appears to have fewer limitations than for snow mapping; at least there are not the complications of rough or heavily-forested terrain encountered in the latter usage. Studies in which photo-interpreation techniques have been used in the analysis of individual satellite pictures indicate that differences of two- to three-eights in pack ice concentration are usually discernible. Refrozen open water areas with new or young ice cover 5 to 15 cm thick appear black, however, and could easily be misinterpreted as open water (Potocsky, 1968). An exception occurs when such a thin ice cover has snow deposited on it (ESSA, 1968, p. 81-82), the ice thereby being rendered visible in the satellite pictures. Perhaps the principal limitation of both individual satellite pictures and satellite CMB charts is lack of solar illumination at high latitudes during the midwinter months. Brightness normalization corrections applied during the digitization process provide more usable high latitude data in the various digital products than are available in the conventional AVCS or APT video pictures. This is because in the digitized pictures the brightness response is increased in proportion to the decreased solar illumination at higher latitudes (Bristor et al., 1966). The digitized CMB charts have an advantage for ice mapping over digitized picture mosaics for individual days in that they eliminate or suppress transient cloudiness.

Figure 6 is a 5-day CMB chart derived from digitized ESSA 9 satellite data for the period April 14-18, 1969. Figure 7 gives the areas shown as "close or very close pack-ice (7/10-9/10+, incl.)" and "land-fast or continuous field ice (10/10)" on the ice charts published by the United Kingdom Meteorological Office, Marine Division, for the period April 11-20, 1969. The U.K. ice charts are a compilation of ship reports, aerial reconnaissance, and subjective interpretations of individual satellite pictures.

In general there is excellent correspondence between the boundary from the U.K. ice chart (figure 7) and the generally well-defined edge of the high-reflectance areas in the CMB chart (figure 6). Also many smaller irregularities along the ice boundary can be seen in both charts (e.g., see the following areas: Davis Strait; between Iceland and Spitzbergen; the

Barents Sea area east of northern Scandanavia; the northern Sea of Okhotsk area; and the northern Bering Sea area). All of Hudson Bay, Baffin Bay, the waters of the Canadian Archipelago, and the Arctic Ocean south of about 80° N. appear clearly ice locked in the satellite chart; this is confirmed by the U.K. ice chart. The black area poleward of about 80° N. on the CMB chart is data void; here lack of illumination prevented acquisition of satellite data.

Examination of cloud-free, high-resolution satellite pictures of the west coast of Norway and the southern half of the coastlines of the Kamchatka Peninsula during April 14-18 showed high contrast between the snow-covered land and the dark coastal waters. Thus it may be seen in figure 6 that the coastlines electronically superimposed on the imagery in these areas are systematically in error by about 35 km. Overall agreement between figures 6 and 7 is improved if the grid on figure 6 is adjusted accordingly.

When one takes into consideration the coarse resolution of these meso-scale composites, and the distinct probability that the U.K. ice boundaries also are somewhat in error, the agreement is rather remarkable. One may argue, of course, that this consistency is due in part to the fact that satellite data also were used in the construction of the U.K. ice charts. It should be pointed out, however, that the satellite data are used in quite different ways in constructing each of these charts. The individual pictures are interpreted subjectively to discriminate ice from clouds for input to the U.K. ice chart. In the case of the CMB chart the digitized picture data are automatically processed and composited to suppress or remove clouds and to enhance the residual brightness representing snow and ice.

There are a few areas where there is a significant lack of correspondence between figures 6 and 7; one of these is just northeast of the island of Newfoundland. The U.K. ice chart shows the close or very close pack ice extending southward to 50.5° N. in this region, but the edge of what is interpreted as ice in the CMB chart appears no farther south than about 52° N., a discrepancy of about 150 km. A similar discrepancy may be noted off the southwest tip of Greenland. Here the U.K. ice chart indicates that the pack ice boundary in this area was determined by aircraft radar on April 18. Yet a third area where the CMB chart[5] indicates less ice area than the U.K. chart is in the Barents Sea near 40°E. It is noteworthy that in all these areas with significant differences between the two charts the CMB chart appears dark, indicating that on at least one day of the compositing period these areas were free of both clouds and ice. This was confirmed by inspection of the daily, full resolution satellite pictures. So it appears that any sizable discrepancies there are between figures 6 and 7 are explicable in terms of the somewhat different bases of preparation of the two charts. The U.K. chart is a simple 10-day composite of all available ice observations, whereas the satellite CMB chart is a composite of the minimum brightness at each spot over a 5-day period. Thus, in the absence of cloud over a given

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[5]The U.K. ice chart carried the notation "18 April satellite" in this area. A check of the satellite pictures for this day showed that the ice boundary was transcribed onto the U.K. chart incorrectly (i.e., the west-east boundary of the pack-ice should have been placed nearly 80 km farther poleward).

area, unless ice is present every day of the compositing period, it cannot appear in the CMB chart. Movement of ice out of an area during the period, for instance, could explain its absence there on the CMB chart.

Some interesting variations in brightness are evident within certain regions or from one region to another in figure 6. For instance, the ice pack east of Greenland is distinctly less bright poleward of about 72° N. and east of 40° E. than it is elsewhere generally; the ice in the Sea of Okhotsk also exhibits large variations in brightness. More experience with CMB charts and better verifying data will be needed to ascertain whether such differences in brightness can be interpreted reliably in terms of specific ice conditions.

Most of the larger areas shown as "new, rotten, or brash" ice on the U.K. ice chart appear dark on the CMB chart. Examples are found along the northern edge of the Sea of Okhotsk, including the Gulf of Shelekhova west of Kamchatka; and in the Norton Sound area just off the coast of western Alaska. Some of the smaller areas of much thinner or non-solid ice, or the narrower openings that are termed "leads," are either not discernible in figure 6 or they appear merely as distinctly grayer areas (e.g., along the west coast of Novaya Zemlya, the southeast coast of Ellesmere Island, the west coast of Greenland at about 70° N., and the extreme southeastern portion of the Beaufort Sea near Banks Island).

5. CONCLUDING REMARKS

The Composite Minimum Brightness (CMB) chart appears to be an effective tool for large-scale mapping of snow and ice boundaries from satellite video data. Although clouds are not completely filtered by this technique, the amount of residual cloudiness appearing in the composite charts is usually small. Clouds are almost always easily differentiated from snow or ice because the latter are generally brighter and more solid in appearance. Overall accuracy in the placement of snow and ice boundaries from CMB charts appears to be within the limits of uncertainty in positioning these boundaries by conventional observations at the earth's surface.

The principal limitations of the CMB chart stem partly from inherent limitations in positioning of the satellite imagery, partly from the basic weaknesses and lack of on-board calibration in the vidicon camera system, and partly from the compositing technique. Positioning errors often can be corrected by use of landmarks, but since terrestrial features are more readily indentified and accurately positioned when the imagery is high resolution and free of smear, it would be better if this correction could be applied to the daily digitized charts prior to compositing.

Alternative means for display, such as rectified computer printouts of the average brightness for each meso-scale spot, are available and have been produced experimentally. This more quantitative presentation of CMB data has been little used even for research, primarily because of brightness calibration problems.

The use of 15 gray levels is clearly preferable to only five gray levels, especially in forested areas. Another improvement would be the use of

full-resolution instead of meso-scale composites. Roughly this would be a computer product equivalent of the multiple-exposure average brightness chart shown in figure 4, at least in resolution and tonal range, but including the superior cloud filtering characteristics of the meso-scale CMB chart. Experimental full-resolution (64X64 elements per NWP grid square) and so-called "super-mesh" (128X128 elements per NWP grid square) CMB charts with 15 gray tones have been produced recently for limited regions including the United States and Canada. Although positioning errors in the imagery are more troublesome at the higher resolutions, and contamination by fiducial marks also is a problem, these new experimental products appear very promising.

Experiments are underway to find better ways to detect and display time-changes in snow or ice cover with CMB charts. Use of overlapping 5-day periods, for example, enables earlier detection of such changes. Brightness changes from one 5-day period to the next (overlapping or non-overlapping) can be either programmed for CRT film display or mapped directly by computer printout.

In the near future a new generation of improved ESSA satellites will be placed in operation. These satellites will be equipped with a radiometer scanning in the visible part of the spectrum, and there is considerable hope that this sensor will provide better-quality brightness data than is possible with the present video-type system. This, together with more accurate positioning of the imagery, and possibly improvements in data manipulation, promises better satellite surveillance of snow and ice fields in the future.

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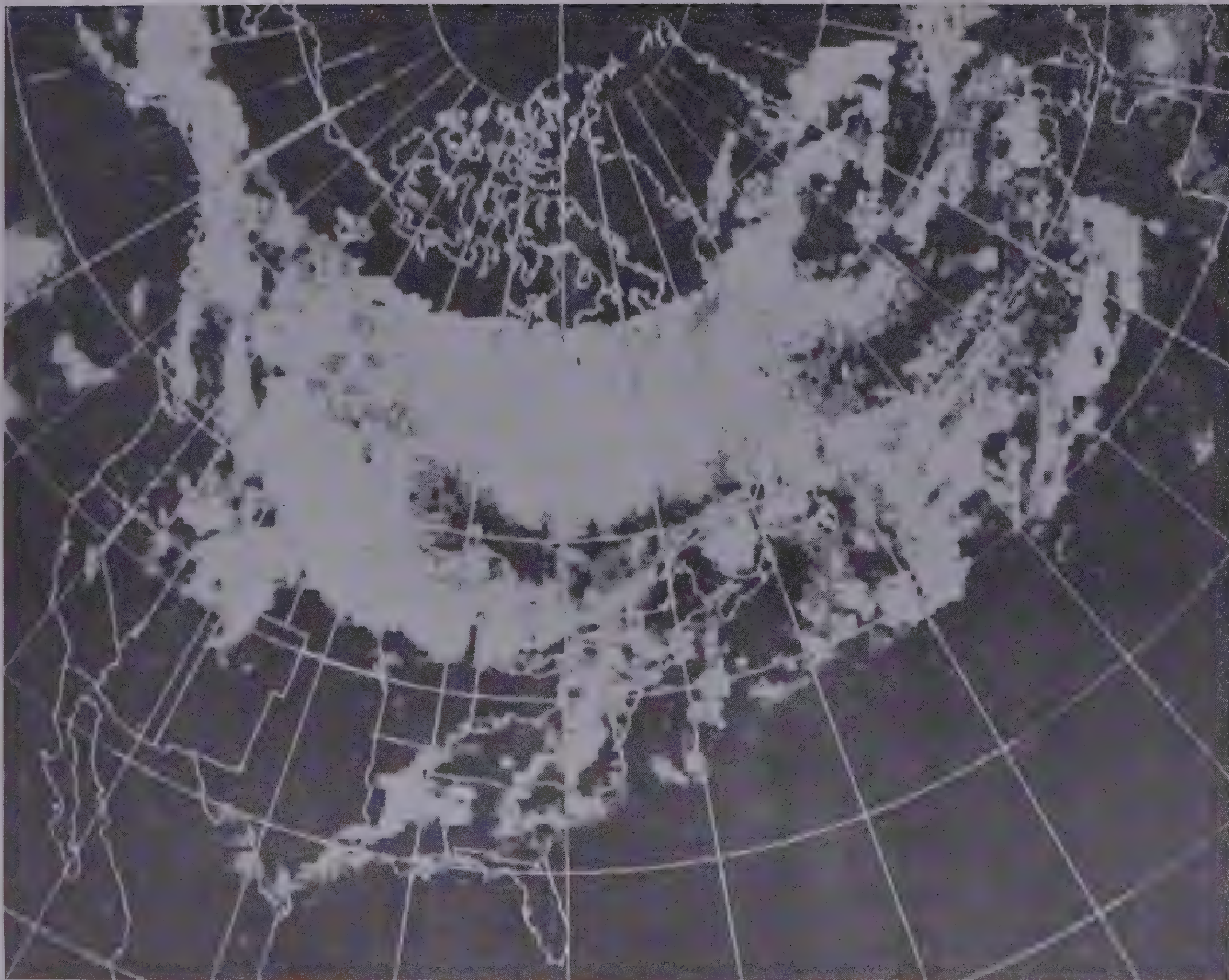

Figure 1.--Three-day Composite Minimum Brightness (CMB) chart for the period February 18-20, 1967. This is a meso-scale digital product derived from ESSA 3 satellite video data and displayed in five gray shades.

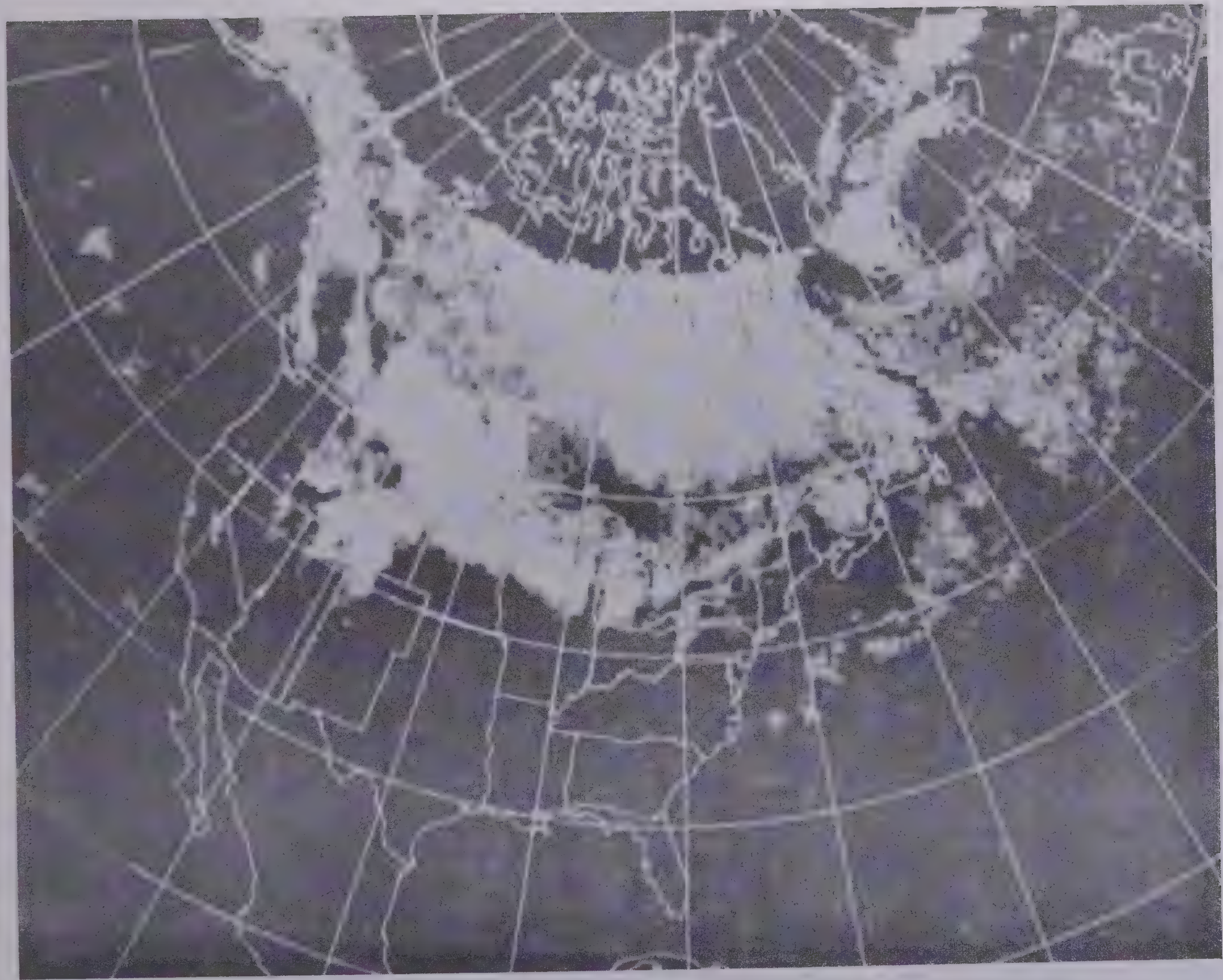

Figure 2.--Five-day CMB chart for the period February 18-22, 1967. This is a meso-scale digital product derived from ESSA 3 satellite video data and displayed in five gray shades.

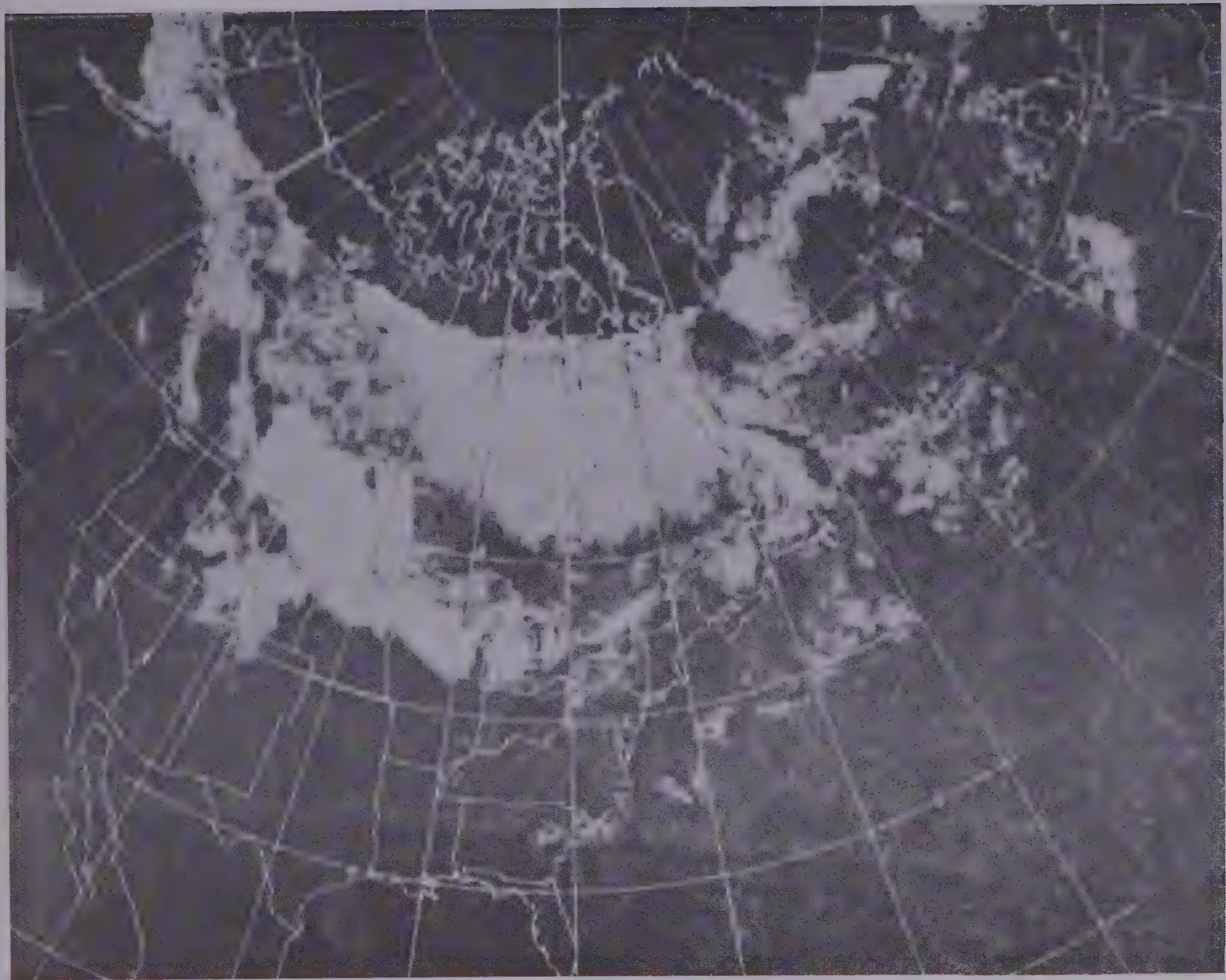

Figure 3.--Seven-day CMB chart for the period February 17-23, 1967. This is a meso-scale digital product derived from ESSA 3 satellite video data and displayed in five gray shades.

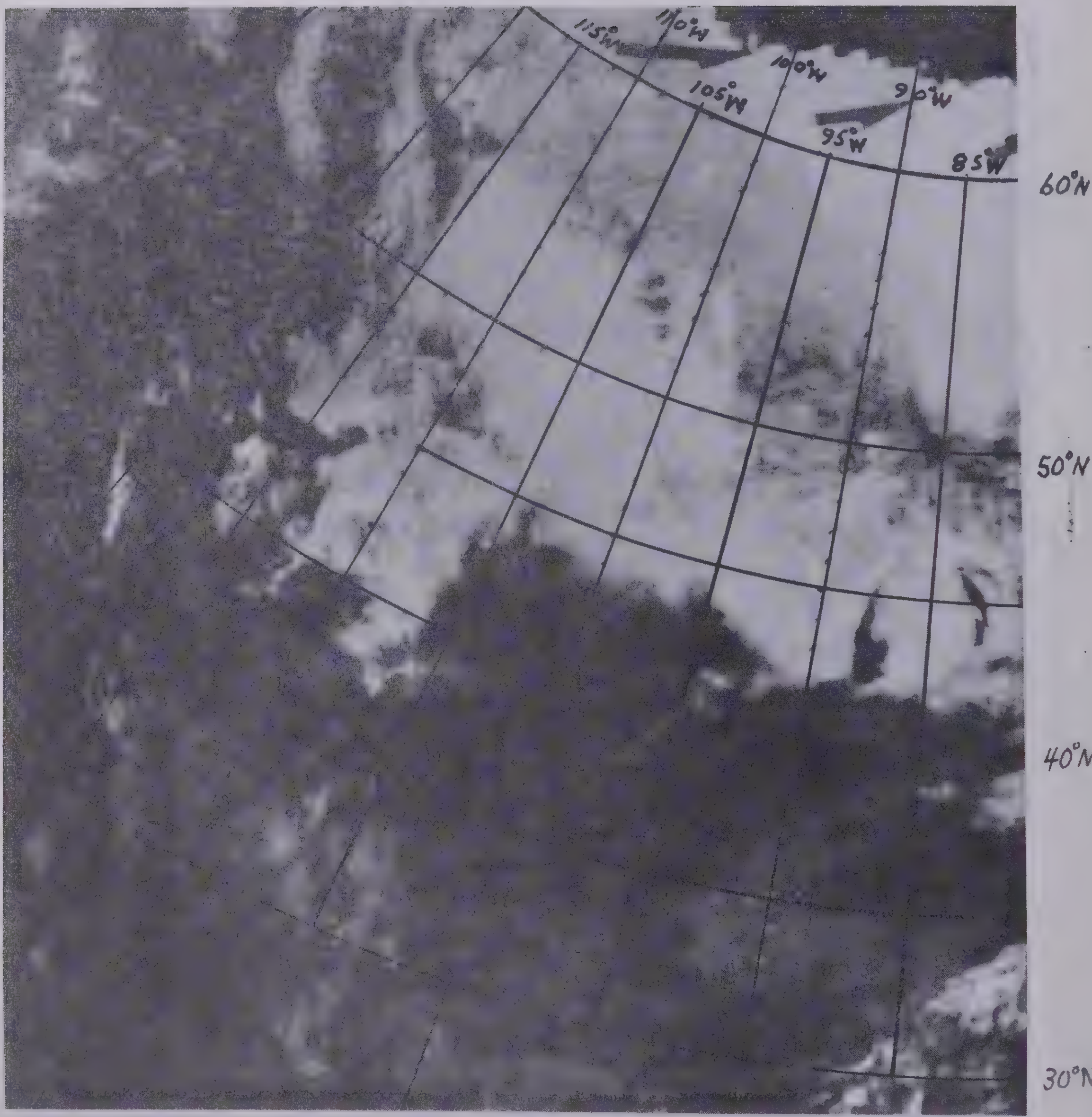

Figure 4.--Five-day average brightness for the period February 18-22, 1967. This chart was obtained by the multiple-exposure method from ESSA 3, full-resolution, digital charts and displayed in fifteen gray shades.

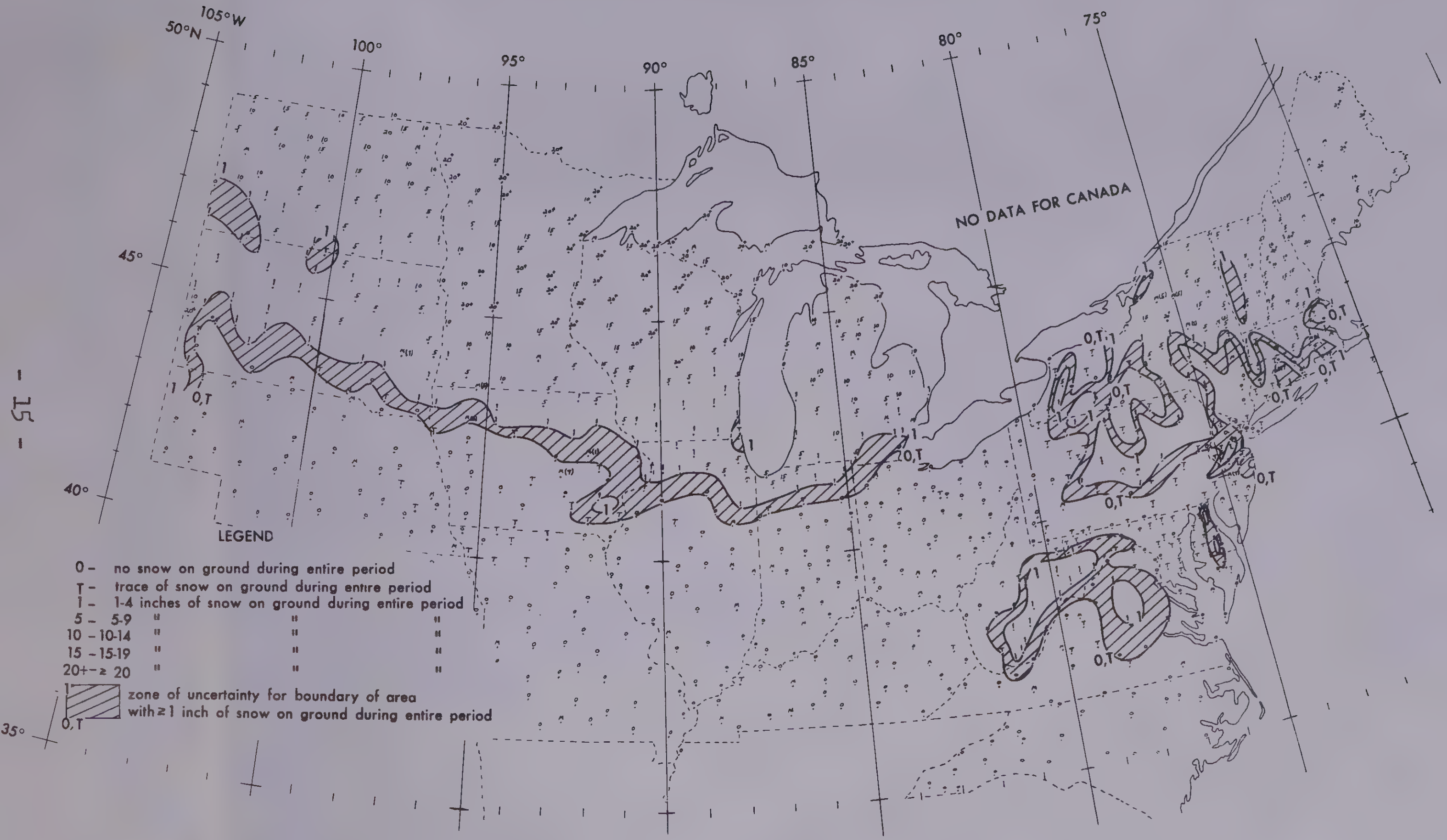

Figure 5.--Composite snow cover chart for the period February 18-22, 1967, based on ground observations.

Figure 6.--Five-day CMB chart for the period April 14-18, 1969. This is a meso-scale digital product derived from ESSA 9 satellite video data and displayed in fifteen gray shades.

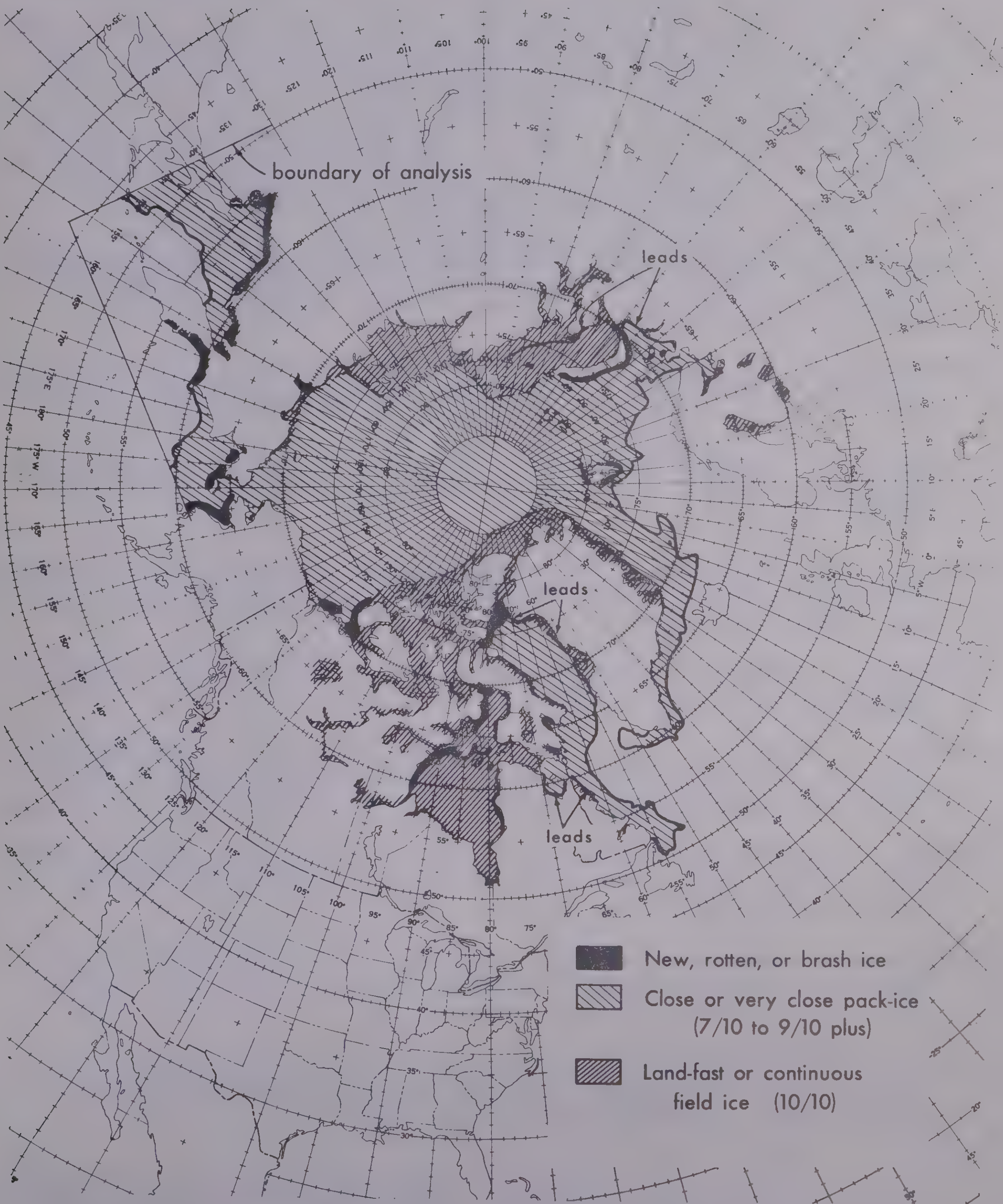

Figure 7.--United Kingdom ice chart for the period April 11-20, 1969, based on ship, aircraft, and satellite data.

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